Estimates for Forward-backward Asymmetry in $B \to K^*(892)\, l^+ l^-$

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(Sept., 1994)

Abstract

Forward-backward charge asymmetry in rare dilepton B-decays is formulated with the assumption of an on-shell b-quark. We find the asymmetry is expressed in terms of two spatially transverse helicity amplitudes, which are determined by combining the data of $D \to K^*(892)\, l^+\nu$ with heavy flavour symmetry. We estimate the charge asymmetry of $B \to K^*(892)\, l^+l^-$ for large energy leptons against various top masses in the standard model.

I. INTRODUCTION

Rare B-decays have been the focus of many experimental and theoretical considerations [1,2]. This is due to the amount of information concerning the standard model (SM) that can be extracted from these processes. The rare decays proceed through flavour changing neutral current (FCNC) vertices which are absent at the tree level and thus provide a good probe of the SM at the quantum (loop) level. On the other hand, rare B-decays are sensitive to quark mixing angles V_{td}, V_{ts} and V_{tb}, hence their determination will yield valuable information on CKM matrix elements and consequently shed some light on CP violation in the SM. These processes are also dependent on the top quark mass m_t through the dominant internal top quark line so that a comparison between theoretical estimates as a function of m_t and experiment may lead to constraints on the top quark mass. In this letter we focus on the rare decays $B \to K^* l^+ l^- (l = e, \mu)$.

The motivation for this work comes from the observation that for rare decays $b \to s\ l^+ l^-$ (which proceed through γ, Z and $W^\pm$ exchange diagrams) forward-backward charge asymmetry of dilepton production has the potential to be fairly large in the SM [3]. For $m_t/M_W \geq 2$, as suggested by the CDF value of $m_t = 174 \pm 17$ GeV, the contribution of the Z-exchange diagrams becomes important, leading to a substantial asymmetry. Such an asymmetry in inclusive $B \to X_s\ l^+ l^-$ processes has been recently studied in the SM and some non-standard models [4]. Consequently, we feel that similar investigations should be carried out on *exclusive* rare B-decays. In particular, we hope to examine the sensitivity of forward-backward asymmetry to the top mass and extensions of the SM. A main source of uncertainty in all such studies has been the evaluation of hadronic matrix elements (HME) for specific exclusive decays. Such evaluations involve long range nonperturbative QCD effects which render the calculations model dependent. During the past few years there has been considerable progress in formulating HME for cases in which the mesons contain a heavy quark [5–7]. For example, if the c-quark is treated heavy along with the b-quark, all the form factors parameterizing the HME for heavy to light $0^- \to 0^-$ and $0^- \to 1^-$ processes can be

written in terms of a set of six universal form factors which represent the underlying QCD dynamics [8,9]. These form factors carry the heavy flavour symmetry and are independent of quark current operators. Thus they permit the model independent study of *exclusive* B decays into light flavour mesons in the small recoil region. In the rare dilepton B-decays, it is necessary to restrict oneself to a dilepton invariant mass well below the J/ψ-mass or above the ψ'-mass to avoid the resonance background. As far as the $B \to K^* l^+ l^-$ channel is concerned, the forward-backward asymmetry expressed in terms of spatially transverse form factors is suppressed as one tends toward smaller dilepton masses (see Eq. (5)). In this letter, we shall concentrate on regions close to the maximum value of the dilepton mass . We shall firstly formulate forward-backward charge asymmetry in rare dilepton B-decays. Secondly, using the assumption of an on-shell b-quark, we demonstrate that the asymmetry is determined by two helicity amplitudes $h_\pm$. Further, combining the data of $D \to K^*(892)\ l^+\nu$ for individual form factors with heavy flavour symmetry, we estimate the asymmetry of $B \to K^*(892)\ l^+ l^-$ for several top masses. Finally, we present discussions concerning our numerical results and comment roughly on the potential signatures of new physics in rare dilepton B-decays.

II. FORMULAE OF FORWARD-BACKWARD ASYMMETRY

Let us begin with an effective Hamiltonian relevant to flavour-changing one-loop processes $b \to s l^+ l^-$ [10]

$$H_{eff} = \frac{G_F}{\sqrt{2}} \left(\frac{\alpha}{4\pi s_W^2} \right) [\bar{s}\Gamma^A_\mu b\ \bar{l}\gamma^\mu(1-\gamma_5)l + \bar{s}\Gamma^B_\mu b\ \bar{l}\gamma^\mu(1+\gamma_5)l], \tag{1}$$

with effective vertices

$$\Gamma^{A(B)}_\mu = A(B)\gamma_\mu(1-\gamma_5) - i m_b s_W^2 F_2 \sigma_{\mu\nu} q^\nu (1+\gamma_5)/q^2.$$

In this Hamiltonian, heavy particles, $W^\pm$-bosons and the top quark are integrated out and their masses together with QCD corrections are absorbed into coefficient functions,

$$A(B, F_2) = \sum_{q=u,c,t} V_{qs}^* V_{qb} A_q(B_q, F_2^q), \tag{2}$$

which are dominated in the SM by the top quark contributions, except for the long distance effect which proceeds mainly through CKM favored $c\bar{c}$ intermediate vector meson states. Here V_{qs} and V_{qb} are elements of the CKM matrix and $A_q(B_q, F_2^q)$ are given in ref. [10–12]. The effective quark current $\bar{s}\Gamma_\mu^{A(B)}b$ in question has two different structures; the parametrization for the matrx element of $V-A$ currents in terms of invariant form factors is

$$\begin{aligned} \langle p, \phi | \bar{s}\gamma^\mu(1-\gamma_5)b|P\rangle = \; & [a_+(q^2)(P+p)_\mu + a_-(q^2)(P-p)_\mu]P^\nu\phi_\nu^* \\ & + f(q^2)\phi_\mu^* + ig(q^2)\epsilon_{\mu\nu\alpha\beta}\phi^{*\nu}P^\alpha p^\beta. \end{aligned} \tag{3}$$

In analogy to this we have for the magnetic-moment operator

$$\begin{aligned} -\frac{i}{q^2}\langle p, \phi | \bar{s}\sigma_{\mu\nu}q^\nu(1+\gamma_5)b|P\rangle = \; & [\tilde{a}_+(q^2)(P+p)_\mu + \tilde{a}_-(q^2)(P-p)_\mu]P^\nu\phi_\nu^* \\ & + \tilde{f}(q^2)\phi_\mu^* + i\tilde{g}(q^2)\epsilon_{\mu\nu\alpha\beta}\phi^{*\nu}P^\alpha p^\beta, \end{aligned} \tag{4}$$

along with a condition of current conservation,

$$(M^2 - m^2)\tilde{a}_+ + q^2\tilde{a}_- + \tilde{f} = 0.$$

Here M (P_μ) and m (p_μ) are masses (momenta) of parent and daughter mesons, respectively, ϕ_μ the polarization vector of daughter mesons (satisfying $\phi_\mu p^\mu = 0$) and $q = P - p$ the momentum transfer into the dilepton.

The differential forward-backward asymmetry of the l^+ that we are to study is defined by

$$d\Gamma_{FB}(q^2) = \int_0^1 d\Gamma(\cos\theta_l) - \int_{-1}^0 d\Gamma(\cos\theta_l),$$

in which $\pi - \theta_l$ is the polar angle of the l^+ with respect to the direction of motion of the decaying meson in the l^+l^--frame. It can be derived from the decay distribution in ref. [9]

$$\frac{d\Gamma_{FB}}{dq^2} = \frac{1}{64\pi^3}\left(\frac{G_F}{\sqrt{2}}\right)^2 \mid V \mid^2 \frac{\lambda\, q^2}{M^2}[(\mid H_+^L \mid^2 - \mid H_-^L \mid^2) - (\mid H_+^R \mid^2 - \mid H_-^R \mid^2)], \tag{5}$$

where $\lambda = \sqrt{(v\cdot p)^2 - m^2}$ is a measure of the recoil and turns out to be the magnitude of the momentum of the daughter meson in the parent rest frame with $v \cdot p = \dfrac{1}{2M}(M^2 + m^2 - q^2)$.

As long as the u-quark is ignored, one has $\mid V \mid = \frac{\alpha}{4\pi s_W^2} \mid V_{cs}^* V_{cb} \mid$ from unitarity of the CKM matrix. The helicity amplitudes appearing here are defined as

$$H_\pm^{L(R)} = \sum_{q=c,t} A_q(B_q) h_\pm + m_b s_W^2 F_2^q \tilde{h}_\pm, \tag{6}$$

where $h_\pm \equiv f \pm \lambda M g$ and $\tilde{h}_\pm \equiv \tilde{f} \pm \lambda M \tilde{g}$. In Eq. (5) we set the limit of $m_l = 0$ and therefore there is no mixture between left- and right-handed leptons. The small lepton mass only manifests itself at the lower boundary $q^2 = 4m_l^2$ logarithmically, but since we are only interested in the region near the upper boundary, we may safely use such a limit. Assuming the B-meson contains an on-shell b-quark, one finds

$$\tilde{h}_\pm = \frac{1}{q^2}(M - v \cdot p \mp \lambda)\; h_\pm, \tag{7}$$

(see the Appendix for detailed dicussion). This leads us into helicity amplitudes

$$H_\pm^L = (A + m_b s_W^2 F_2 \frac{M - v \cdot p \mp \lambda}{q^2})\; h_\pm, \tag{8}$$

$$H_\pm^R = (B + m_b s_W^2 F_2 \frac{M - v \cdot p \mp \lambda}{q^2})\; h_\pm. \tag{9}$$

For comparision, we also present the transverse distribution of the decay rate

$$\frac{d\Gamma_T}{dq^2} = \frac{1}{48\pi^3} \left(\frac{G_F}{\sqrt{2}}\right)^2 |V|^2 \frac{\lambda\, q^2}{M^2} [(\mid H_+^L \mid^2 + \mid H_-^L \mid^2) + (\mid H_+^R \mid^2 + \mid H_-^R \mid^2)]. \tag{10}$$

We emphasize that all forms presented here also hold for B-decays into higher K-resonances [9].

III. HELICITY FORM FACTORS AND NUMERICAL RESULTS

Isgur and Wise [8] have suggested using heavy flavour symmetry to relate the form factors for $B \to K^* l^+ l^-$-decays with those for semileptonic D-decays having the same meson, i.e. $K^*(892)$ in the final state. However, in the e and μ-channels of D-decays it is difficult to measure the V-A form factor a_- as it is suppressed by m_l^2/q^2. Consequently, it is hard

for one to obtain the form factor $\tilde{a}_+$ (or $\tilde{a}_-$) in the rare B-decays using this method. But we are indeed allowed to determine those form factors occuring in the asymmetry when we concentrate on the small recoil region. Burdman and Donoghue have instead used $SU(3)$ light flavour symmetry to relate rare B-decays with semileptonic B-decays [13]. In this letter we will use the approach of Isgur and Wise and the form factors A_1 and V (proportional to f and g, respectively) of $D \to K^*(892)\ l^+\nu$ processes measured by E691, E687 and CLEO groups [15]. All of these groups assume the nearest pole dominance for the q^2-dependence of form factors. Since the range of q^2 in this decay is only about 1 GeV^2 (small compared to heavy pole masses), the resulting form factors are not sensitive to the parameterization of the q^2-dependence.

In the leading order of heavy quark effctive theory, form factors scale as

$$h_\pm = \left[\frac{\alpha_s(m_b)}{\alpha_s(m_c)}\right]^{-6/25} \sqrt{\frac{M}{M_D}}\, h_\pm^D. \tag{11}$$

In this equation helicity amplitudes are evaluated at the same $v \cdot p$, namely that $h_\pm$ at $q^2 = M^2 + m^2 - 2Mv \cdot p$ are related to $h_\pm^D$ at $q_D^2 = M_D^2 + m^2 - 2M_D v \cdot p$. The region in which heavy quark symmetries can be applied to weak decays may be determined by the average momentum transfer Q_l of the light degrees of freedom. It is estimated heuristically for $D \to K^*$ decay by [16] that

$$Q_l^2 < \frac{m_q}{m}\frac{m_q}{M_D}(M_D - m)^2 \simeq (0.13 M_D)^2,$$

with light quark mass $m_q = 330$ MeV. Thus we expect the heavy flavour symmetry to be a reliable approximation in the whole physical range of $q_D^2 = [0,\ (M_D - m)^2]$, corresponding to $q^2 = [q_0^2,\ (M - m)^2]$ in $B \to K^*$ modes. Here the lower limit $q_0^2 = (4.07\ \mathrm{GeV})^2$ serves as an experimental cut-off for the avaliable data and restricts us to a range that is away from the peaks of J/ψ and ψ' and above the $c\bar{c}$ threshold. Thus decay distributions are dominated by the top quark plus the continuum $c\bar{c}$ involved via four-qaurk operators. With the coefficients given in ref. [11] and the parameters listed below, we integrate forward-backward asymmetry, along with the transverse decay rate, in the momentum interval of

$[q_0^2,\ (M-m)^2]$. The numerical results for representative top masses are shown in Table 1. Like in ref. [14], both the asymmetry and decay rate are normalized to $\Gamma_0 = \Gamma(B \to X_s\ J/\psi) Br(J/\psi \to l^+\ l^-)$, using the experimental input $Br(B \to X_s\ J/\psi) = (1.09 \pm 0.04)\%$ [18] and $Br(J/\psi \to l^+\ l^-) = (5.98 \pm 0.25)\%$ [19].

Although we believe that reliable estimates for the asymmetry are provided in the stated kinematic region, we need an alternative prescription to determine helicity amplitudes. This will enable us to probe decay distributions below q_0^2 for the sake of increasing the statistics. In this situation Eq. (11) is only used to gain $h_\pm$ at a q_m^2 which is approaching to, but not identical with, the maximum value of $q^2 = (M-m)^2$ where $h_+ = h_-$. It seems appropriate in the small recoil region of $B \to K^*$ decays to approximate the q^2-dependence of form factors by the nearest pole dominance

$$\left(1 - \frac{q^2}{M'^2}\right)\ h_\pm(q^2) = \left(1 - \frac{q_m^2}{M'^2}\right)\ h_\pm(q_m^2), \tag{12}$$

as the end-point is close to the pole. Here M' is instead a pole mass of the current involving b- and s-quarks and we will make no distinction between the vector and axial masses. As a check, we first evaluate the integrated asymmetry with helicity amplitudes in Eq. (13) over the interval of $[q_0^2,\ (M-m)^2]$. The numerical results give a difference within 5% (7% for transverse decay rate), from that with Eq. (11). This provides us confidence to extrapolate the data of D-decays to the region below q_0^2 but above the $D\bar{D}$ continuum threshold $q_1^2 = (3.74\ \text{GeV})^2$. Table 2 is devoted to numerical integrals over $[q_1^2,\ (M-m)^2]$. The contributions to decay distributions of individual helicity amplitudes are illustrated in Fig. 1 for the left-handed lepton and in Fig. 2 for the right-handed lepton .

The parameters that appear in our calculations are taken as (in GeV for masses)

$$M = 5.28, \quad M_D = 1.87, \quad m = 0.892, \quad M(D_s^*) = 2.11, \quad M(D_{s1}) = 2.54,$$

$$s_W^2 = 0.233, \quad |\ V_{ts}^* V_{tb}\ | = |\ V_{cs}^* V_{cb}\ | = 0.044, \quad m_b = 4.9, \quad m_c = 1.5, \quad M' = 5.42.$$

IV. DISCUSSIONS

We shall now interprete the numerical results qualitatively. Firstly we recall that it is well confirmed in semileptonic $B \to D^*$ and $D \to K^*$ that $|\,h_-\,|>|\,h_+\,|$. An analogous relationship that the (transverse) negative helicity of the K^* dominates over the positive one, i.e. $|\,H_-^{L(R)}\,|>|\,H_+^{L(R)}\,|$ is found in the regions we have considered for dilepton rare decays. This is because the s-quark produced by the effective hamiltonian in Eq. (1) is of predominantly negative (or left-handed) helicity. Upon hadronization, the s-quark picks up a spectator quark having both helicities with equal probability and thus forms a K^* in favour of the negative one. Actually, the contribution of $H_-^{L(R)}$ differs dramatically from that of $H_+^{L(R)}$ due to the large mass of the B-meson. Secondly with no four-quark operator mixing in, we have the SM values of the coefficient functions in Eq. (2)

$$A_t = 1.94, \quad B_t = -0.136, \quad s_W^2 F_2^t = -0.141, \tag{13}$$

for the effective vertices at $m_t = 174$ GeV. The QCD corrections are partly responsible for the small coupling of the right-handed lepton. Obviously, left-handed leptons dominate the final state. This feature is common to all top mass cases listed in Table 1. As the four-quark operator $\bar{s}\gamma_\mu(1-\gamma_5)b\,\bar{c}\gamma^\mu(1-\gamma_5)c$ enters through a vector current and shifts both A and B by about 0.1, there is very little change in the chirality pattern. We should remind ourselves that the mixing of other four-quark operators is even smaller [11,20], so the chirality of leptons represented by Eq. (13) strongly influences the resulting decay distribution. As a final word, we realize that H_+^R suffers from both helicity and QCD suppression and is thus negligble, H_+^L is largely suppressed by helicity and H_-^R is only reduced by the QCD correction. Hence, the chirality of both quarks and leptons determined by the SM remains clearly manifested in exclusive processes; the forward-backward charge asymmetry is negative, sensitive to the magnitude of H_-^L. With a relative small effect for right-handed leptons, the asymmetry does not differ from the transverse decay rate too much. Given a longitudinal helicity amplitude which is not particularly large, the decay distribution in the regime near the zero recoil

comes mainly from transverse helicity amplitudes due to a q^2 enhancement. In other words, the magnitude of the asymmetry is expected to be comparable with the decay rate, to which we refer as a large aymmetry of lepton production predicted by the SM in $B \to K^*\ l^+l^-$ processes.

To obtain more precise results, we must account for the deviation from the heavy flavour symmetry due to finite masses of b- and c-quarks. The leading corrections to the ratio of form factors in $B \to \rho\ l\bar{\nu}$ to that in $D \to \rho\ l\bar{\nu}$ are evaluated at the end-point in the framework of a constituent quark model [21]. It is found that the deviation from the limit of $m_Q \to \infty$ is encouragingly small, being of order 15%. With this indication we assume modification of a similar size for the $B \to K^*\ l^+l^-$ decay. Such an analysis will be reported elsewhere.

We conclude with a number of comments on potential signals of new physics beyond the SM in rare dilepton B-decays. Recent measurments of $B \to X_s\gamma$ by the CLEO group [1] result in a constraint on the magitude of F_2 [4]

$$0.44 \geq |F_2| \leq 0.60,$$

which is close to the value of the SM. The sign of F_2 is irrelevant to radiative processes, but is important in dilepton decays because of interference. In the SM, F_2 is negative relative to A and contrastly new physics may manifest itself if a positive one of similar size was allowed [22]. Such an F_2 would produce an enhancement of about factor 1.5 in the asymmetry and the decay rate. Meanwhile, any different input of both the magnitude and the sign for A and B from that of the SM will lead to visible changes to the forward-backward asymmetry as well as the decay rate in rare dilepton decays. It is, however, interesting to describe a special possibility in which the importance of left-handed leptons is replaced by right-handed leptons. While it is possible for the decay rate not to be sensitive to the change, the large negative asymmetry will be turned into a positive one. In such a case, it is the measurment of the asymmetry that tells us about new physics. Alternatively, if the asymmetry were small, our estimates should fail to be reliable, as corrections from the quark mass would show up

when different contributions in Eq. (5) would tend to cancel each other. Fortunately, this is not the case in the SM. Nevertheless, a small asymmetry itself, if measurements find it to be so, can be regarded as a signature of new physics. We are optimistic that current and future B-physics facilities will provide data on rare dilepton decays so that we may test the SM and probe new physics in this sensitive territory.

ACKNOWLEDGMENTS

The author thanks R. Delbourgo for many discussions and encouragement during the work along with P. Jarvis and N. Jones for their help in preparation of this letter. He is also grateful to the Australian Research Council for their financial support, under grant number A69231484.

APPENDIX: RELATIONS OF FORM FACTORS

When a heavy meson contains an on-shell heavy quark the matrix element for the heavy to light transition takes the form [6,7,9]

$$< p,\phi|\bar{q}\Gamma h_v|P\!=\!Mv >= \sqrt{M}\mathrm{Tr}\left[[(G_1+G_2\not{p})v\cdot\phi+(G_3+G_4\not{p})\not{\phi}]\Gamma\frac{1+\not{v}}{2}\gamma_5\right], \qquad \text{(A1)}$$

with Γ an arbitrary matrix in Dirac space. The invariant overlap integrals G_i are functions of $v\cdot p$ and bear the heavy quark symmetry. Comparing Eq. (3) and Eq. (4) in the main text to traces with $\Gamma=\gamma_\mu(1-\gamma_5)$ and $\sigma_{\mu\nu}q^\nu(1+\gamma_5)$ gives

$$\begin{pmatrix} f \\ g \end{pmatrix} = -2\sqrt{M}\begin{pmatrix} 1 & -v\cdot p \\ 0 & \dfrac{1}{M} \end{pmatrix}\begin{pmatrix} G_3 \\ G_4 \end{pmatrix}, \qquad \text{(A2)}$$

and

$$\begin{pmatrix} \tilde{f} \\ \tilde{g} \end{pmatrix} = \frac{2\sqrt{M}}{q^2}\begin{pmatrix} -(M-v\cdot p) & M(v\cdot p)-m^2 \\ \dfrac{1}{M} & -1 \end{pmatrix}\begin{pmatrix} G_3 \\ G_4 \end{pmatrix}, \qquad \text{(A3)}$$

respectively. Then removing G_3 and G_4 we find

$$\begin{pmatrix} \tilde{f} \\ \lambda M \tilde{g} \end{pmatrix} = \frac{1}{q^2} \begin{pmatrix} M - v \cdot p & -\lambda \\ -\lambda & M - v \cdot p \end{pmatrix} \begin{pmatrix} f \\ \lambda M g \end{pmatrix}, \tag{A4}$$

agreeing with that of ref. [8]. Futhermore, transforming into transverse helicity amplitudes, $h_\pm = f \pm \lambda M g$ [17] and $\tilde{h}_\pm = \tilde{f} \pm \lambda M \tilde{g}$, diagonalizes the relation with eigenvalues $M - v \cdot p \mp \lambda$. This leaves

$$\tilde{h}_\pm = \frac{1}{q^2}(M - v \cdot p \mp \lambda)\, h_\pm. \tag{A5}$$

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Table captions:

Table 1 The integrated asymmetry and transverse decay rate (in 10^{-4}) over the region of $q^2 = [q_0^2,\ (M-m)^2]$ with helicity amplitudes determined by the data of $D \to K^*(892)\ l^+\nu$ (see Eq. (11) of the main text). All entries are normalized to $\Gamma_0 = \Gamma(B \to X_s\ J/\psi) Br(J/\psi \to l^+\ l^-)$.

Table 2 The asymmetry and transverse decay rate (in 10^{-4}) integrated over the region of $q^2 = [q_1^2,\ (M-m)^2]$ with helicity amplitudes determined by combining the data of $D \to K^*(892)\ l^+\nu$ with nearest pole domination (see Eq. (13) of the main text). The normalization is the same as Table 1.

Figure captions:

Figure 1 Decay distributions $\dfrac{1}{\Gamma_0}\dfrac{d\Gamma_\pm}{ds} \times 10^4$, for the left-handed lepton in terms of the negative (dot-dashed line) and positive (solid line) helicity amplitudes, for which Eq. (13) is used. We define that $s = q^2/M^2$ and vertical dashed lines at $s = 0.488,\ 0.501,\ 0.594$ indicate ψ'-peak, $D\bar{D}$-threshold and $q_D^2 = 0$, respectively. The top mass is taken as $m_t = 174$ GeV.

Figure 2 The same as Fig. 1 for the right-handed lepton.

TABLES

Top mass (GeV)	$\Gamma_{FB}^{(L)}$	$\Gamma_{FB}^{(R)}$	Γ_{FB}	$\Gamma_{T}^{(L)}$	$\Gamma_{T}^{(R)}$	Γ_{T}
131	-0.213	-0.002	-0.211	0.374	0.003	0.377
150	-0.288	-0.015	-0.273	0.506	0.025	0.531
174	-0.378	-0.008	-0.359	0.644	0.013	0.658
200	-0.501	-0.026	-0.475	0.877	0.043	0.920

Table 1.

Top mass (GeV)	$\Gamma_{FB}^{(L)}$	$\Gamma_{FB}^{(R)}$	Γ_{FB}	$\Gamma_{T}^{(L)}$	$\Gamma_{T}^{(R)}$	Γ_{T}
131	-0.578	-0.004	-0.573	0.857	0.007	0.863
150	-0.748	-0.006	-0.742	1.11	0.01	1.12
174	-0.999	-0.025	-0.975	1.48	0.04	1.52
200	-1.36	-0.08	-1.29	2.02	0.11	2.12

Table 2.